AFRL-RV-PS-
TR-2012-0191

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TR-2012-0191

A NEW METHOD FOR COUPLING THE POTENTIAL FIELD SOURCE SURFACE AND THE SCHATTEN CURRENT SHEET MODELS

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24 September 2012

Final Report

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REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. REPORT DATE *(DD-MM-YYYY)*
24-09-2012

2. REPORT TYPE
Final Report

3. DATES COVERED *(From - To)*
02 Sep 2008 to 24 Sep 2012

4. TITLE AND SUBTITLE

A NEW METHOD FOR COUPLING THE POTENTIAL FIELD SOURCE SURFACE AND THE SCHATTEN CURRENT SHEET MODELS

5a. CONTRACT NUMBER
FA8718-08-C-0024

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER
62601F

6. AUTHOR(S)

Leslie R. Mayer

5d. PROJECT NUMBER
1010

5e. TASK NUMBER
PPM00005108

5f. WORK UNIT NUMBER
EF004318

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
University of Colorado
Cooperative Institute for Research in Environmental Sciences (CIRES)
216 UCB
Boulder, CO 80309

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES)

Air Force Research Laboratory
Space Vehicles Directorate
3550 Aberdeen Ave SE
Kirtland AFB, NM 87117-5776

10. SPONSOR/MONITOR'S ACRONYM(S)

AFRL/RVBXS

11. SPONSOR/MONITOR'S REPORT NUMBER(S)
AFRL-RV-PS-TR-2012-0191

12. DISTRIBUTION / AVAILABILITY STATEMENT

Approved for public release; distribution is unlimited. (377ABW-2012-1309 dtd 27 Sep 12)

13. SUPPLEMENTARY NOTES

14. ABSTRACT
The Wang-Sheeley-Arge (WSA) model describes the magnetic field configuration of the corona and is used, in combination with other models, to predict the global solar wind out past earth days in advance. It is routinely used for both AF and civilian space weather forecasting purposes. WSA is comprised of two coupled models: (1) the Potential Field Source Surface (PFSS) model with a domain extending out to several solar radii above the Sun's surface and (2) the Schatten Current Sheet (SCS) model used to project the solution out into the hypersonic interplanetary flow regime some 20 Rs or more above the solar surface. Three major and several minor improvements have been made to the Wang-Sheeley-Arge (WSA) coronal model that remedies well known model weaknesses and problems. These changes, described in this final report, significantly improve the model's predictive performance and further enhance its usefulness as a space weather forecast model.

15. SUBJECT TERMS
Corona, Solar Wind, Potential Field Source Surface model, Schatten Current Sheet model

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
					Charles N. Arge
a. REPORT	b. ABSTRACT	c. THIS PAGE			19b. TELEPHONE NUMBER
UNCLASSIFIED	UNCLASSIFIED	UNCLASSIFIED	SAR	18	505-846-1965

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1. INTRODUCTION

Knowledge of the state of the global solar wind flow in the inner heliosphere (defined as the region inside ~2 AU) is key to accurate space weather prediction. As our civilization becomes increasingly dependent on advanced technology that is often (highly) vulnerable to solar activity, the ability to characterize and foresee potentially hazardous space conditions becomes ever more important.

One of the most effective and versatile tools for diagnosing the global solar wind is the Wang-Sheeley-Arge (WSA) model. [1, 2, 3, & 4] Although many variants exist, the basic model is composed of three parts. First, synoptic maps of the observed solar surface magnetic field distribution are input to a magnetostatic model of the coronal expansion (the potential field source surface algorithm or PFSS), with the domain extending out to several solar radii above the Sun's surface. [5 & 6] An (optional) intermediate model (e.g., the Schatten Current Sheet model or SCS) can then be used to project the solution out into the hypersonic interplanetary flow regime some 20*Rs* or more above the solar surface. [7] Finally, the output of the PFSS (and/or SCS) then feeds into an interplanetary propagation model (e.g., WSA 1-D modified kinematic model, Hakamada-Akasofu-Fry or HAF, or Enlil), which is used to track the resultant flow structures out to Earth and beyond. [3, 8, & 9]

Over the last ten years, the coupled PFSS+SCS model has proven to be more useful overall than the PFSS alone for modeling and predicting the solar wind. This is because 1) the PFSS+SCS model reproduces the observed global field configuration better than the PFSS model alone (i.e., it produces outer coronal solutions with no significant latitudinal gradients in the field, which is consistent with observations); and 2) the PFSS+SCS model allows the coronal field configuration and associated flow speeds to be determined out well past the PFSS source surface location (typically 2.5*Rs*), thereby facilitating the initialization of Magnetohydrodynamic (MHD) solar wind propagation models starting outside the critical point. [10] Nonetheless, the simple PFSS code is useful for determining efficiently the magnetic field configuration in the inner corona and the positions and shapes of corona holes. The PFSS solutions are used widely by scientists doing basic research and serves as input to the current operational version of the HAF model. The PFSS harmonic coefficients are routinely provided to the public on the National Oceanic and Atmospheric Administration's Space Weather Prediction Center (NOAA/SWPC) website as well as directly to Air Force Weather Agency (AFWA).

In 2008 we proposed making a handful of important modifications to the WSA model (i.e., as it existed at the time) that would make it easier to maintain, enhance its predictive performance, and provide new capabilities for space weather applications. We were funded by the Air Force Research Laboratory (AFRL) to make these changes to the model, and this final report summarizes in detail the modifications made.

2. BACKGROUND

At the time of our proposal in late 2008, two separate and rapidly diverging, versions of the WSA were in operation at the Space Weather Prediction Center or SWPC (formerly the Space Environment Center), one running the PFSS alone and the other a combined PFSS+SCS. We proposed producing a single, streamlined, internally consistent code with a switch to allow running in either PFSS or PFSS+SCS mode. In particular, the proposal promised to develop and apply a new modular method for coupling the PFSS and SCS codes. This new feature would result in the need for only one version of the code, as opposed to two, thus making it much more flexible and significantly easier to maintain.

Before our proposal was funded, the WSA code calculated two sets of coronal magnetic field line topologies. First, the code traced magnetic field lines from the outer boundary of the WSA model solution to the solar surface. It did this at the resolution of the model grid by starting each new field line mapping at the cell-centers located on the outer boundary of the model. The resultant magnetic topology is useful for visualizing the overall solar magnetic configuration and for associating upper coronal magnetic structures with near-surface solar features. Second, WSA also calculated a special subset of field lines that intersect the ecliptic plane along the upper boundary of the coronal solution. This subset of field lines provides the basis for predictions of solar wind speed and magnetic polarity for the geospace environment. At the time, the starting points for this mapping were "hard-wired" into the code. We proposed generalizing this capability so predictions at other, non-ecliptic locations, could be made.

The third improvement proposed was the inclusion of the option for tracing magnetic field lines outward from the photosphere to the source surface or outer coronal boundary, depending on which model coupling method was employed (i.e., whether just using the PFSS or the combined PFSS+SCS solution). At the time, the model only permitted the field lines to be traced opposite to this, that is, from the outer coronal boundary to the photosphere. This latter approach is necessary, for it allows the model to uniquely associate every point on the outer surface (i.e., at the center of each grid cell) with a corresponding point on the photosphere, and thus identify those points on the photosphere that are magnetically open to the heliosphere (i.e., the coronal holes). However, depending on the resolution of the grid used, cells on the photosphere are occasionally missed when tracing the field in this manner. Adding the new functionality of tracking the field lines out from the photosphere would eliminate this ambiguity while also permitting the entire (i.e., open and closed) inner coronal field to be mapped.

3. METHODS, ASSUMPTIONS, AND PROCEDURES

Three major and several minor improvements have been successfully made to the WSA model code that greatly enhance its functionality and predictive capabilities. These modifications and changes are now described in detail.

3.1 WSA Modularization

Over the course of this three-year effort the basic structure of the WSA model has been completely reorganized and improved. The potential field source surface (PFSS) and Schatten current sheet (SCS) models (both within WSA) have been fully decoupled and modularized. Before this was done, the code began each new field line mapping by starting at a specified grid cell located on the outer boundary of the model and then tracing that particular magnetic field line down through the SCS portion of the code until it reached the source surface (i.e., the upper boundary of the PFSS model). Once there, the tracing routine jumped to the PFSS portion of the code and resumed the downward field line mapping until it reached the photosphere. The code performed this same procedure for each grid cell on the outer boundary, repeatedly jumping back and forth through the SCS and PFSS solutions, until all field lines were fully mapped.

In the new modularized code, all of the field lines are first traced only through the SCS model domain. That is, each field line is traced from the outer to the inner boundary of the SCS code with the coordinates (i.e., latitude and longitude) of the position (or footpoint) of the field line intersecting the inner boundary of the SCS solution saved to an array in memory. Upon completion of all of the magnetic field line mappings in the SCS model domain, the complete set of magnetic field footpoint positions is then passed on to the PFSS module of the code, where they serve as the set of starting positions of the field mappings through the PFSS model. The mapping process in the PFSS domain proceeds exactly like that just described for the SCS module but now with each new field line tracing beginning on the source surface boundary at the footpoint coordinates determined in the SCS solution and not at the grid cell centers. Each field line is then traced down to the photosphere. This field tracing methodology combined with the newly decoupled PFSS and SCS routines eliminate the need for two independent code versions. In the new WSA code, one can simply set a switch so that in one case the complete PFSS+SCS coupled solution is provided along with the a complete set magnetic field mappings (i.e., both inwardly and outwardly directed), while in the other it is done only for PFSS solution.

3.2 Flexible Method for Inwardly Tracing Sets of Magnetic Field Lines

The WSA code was originally designed to make solar wind predictions only at the location of the Earth. In fact, the positions of the sub-earth point as a function of time were calculated directly within the code itself (i.e., it was “hard wired”), making it difficult to change it so predictions at other points in the heliosphere could be made. To remedy this, a new and flexible method for inwardly tracing sets of magnetic field lines beginning at arbitrary points on the model’s outer coronal boundary (i.e., as opposed to beginning exclusively at grid cell centers) was applied to the WSA code. The locations of the sub-satellite/planet points, for which we want model predictions, are now calculated separately from the main code and placed into a file with a standardized format. The desired sub-satellite/planet positions are then read into WSA as input from one of these files. With this modification a user only needs to obtain an ephemeris of the positions of a satellite or planet as a function of time and then make minor modifications to a script that reads the ephemeris and writes it out in a standardized format. The main control script to WSA can easily be modified so that the program knows which input file to read. Any trajectory through the resultant global solar wind outflow can thus now be sampled and compared to actual spacecraft observations. The new routine has been tested using the STEREO A and B spacecraft locations. Figure 1 shows an example where WSA model solar wind speed predictions (blue dots) are compared to STEREO B observations (solid black line) for Carrington rotation 2089 (i.e., mid-October through mid-November). The red vertical bars indicate the range over which WSA solar wind speed predictions vary over the span (in latitude) of one cell on the grid.

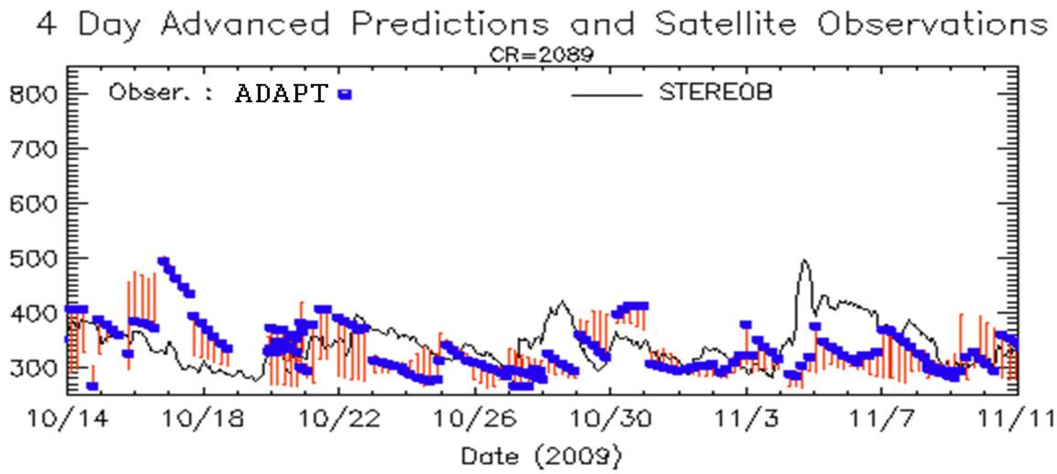

Figure 1. WSA Solar Wind Predictions vs. STEREO B Observations

3.3 Tracing Magnetic Fields Outward from the Photosphere

The third improvement made to the WSA code was the addition of a new routine that traced magnetic field lines outward from the photosphere to the source surface or outer coronal boundary, depending on which coupling method is employed. As mentioned earlier, the original version of the model only permitted field lines to be traced opposite to this, that is, from the outer coronal boundary to the photosphere. However, this particular approach occasionally led to grid cells located at the photosphere being misidentified as being magnetically closed when they were actually open. The addition of this functionality eliminates this problem, since now the magnetic field at each grid cell center on the photosphere is traced upwards to determine conclusively whether it is open or closed. Extensive effort was spent on this aspect of WSA model improvement.

The methodology for tracing the magnetic fields was also improved significantly. Originally the WSA code used a field line tracing approach that was accurate to only first order. The new approach uses a fourth order Runga Kutta tracing scheme that is much more accurate and robust.

3.4 Other Changes

Several other code upgrades were made to the WSA model such as changing variable names to more properly reflect what they represent and modularizing with subroutines so that the code is not repeated. The program was also changed from single to double precision. This was done in order to achieve more accurate computations and more robust field line tracing. Pre-processing and velocity subroutines were changed from IDL to Fortran 95. Work was also performed to improve the tools used to display the WSA model results. For example, solar wind source locations and their corresponding photospheric and outer boundary magnetic field footpoint strengths were added to the 1-7 day WSA solar wind prediction files. This now permits one to simultaneously plot (at most with only slight code modifications) the solar wind observed at Earth against these parameters and thus correlate them with their sources and properties back at the sun. WSA was also modified so that one can readily change the location of the PFSS model's source surface. Several tests were done to confirm the robustness of this coding change. Reality checks for reasonable inputs of the source surface value were included and metadata related to the changing source surface height were added to all output files.

4. RESULTS AND DISCUSSION

The three major and several minor changes made to the WSA code significantly eases the model's long term maintainability, enhances its reliability and robustness, and greatly improves its forecasting and scientific capability. For instance, the new method for coupling the PFSS and SCS program components has resulted in needing only one version of the model code, which makes it much more versatile and significantly easier to maintain. Users can now simply set a switch in the new model version telling it to either calculate the entire combined PFSS+SCS coronal solution or only the PFSS solution. The new and flexible method for inwardly tracing sets of magnetic field lines corresponding to sub-satellite/planet trajectories allows users to easily compare WSA solar wind predictions with observations at different points in the heliosphere. Since the satellite/planetary trajectory emphemerides are now determined outside of the main WSA code, adding new locations for comparison is much simpler. As discussed in Section 3.3, such comparisons have been made at STEREO A & B satellite locations. In fact, WSA solar wind predictions at the locations of STEREO A and B are now automated and routinely available to the public on the web at NOAA/SWPC (helios.swpc.noaa.gov/wsa/stereo).

Adding the capability of mapping the field lines outward from the photosphere into the corona greatly improves the model's ability to accurately predict the sizes, shapes, and positions of coronal holes and thus the solar wind. As discussed in Section 3.3, WSA originally only traced coronal magnetic fields starting from the source surface/outer coronal boundary down to the photosphere. This simple approach was originally used for it allowed the model to uniquely associate every point on the outer surface (i.e., at the center of each grid cell) with a corresponding point on the photosphere. The ability to do this is important for two reasons. First, the magnetic flux tube expansion factor (f_s) was, long ago, found to be empirically correlated with solar wind speed. [1] Flux tube expansion is calculated using the traditional definition $f_s = (R_{ph}/R_{ss})^2[B_{ph}/B_{ss}]$, where B_{ph} and B_{ss} are the field strengths, along each flux tube, at the photosphere ($R_{ph} = 1R_s$) and the source surface($R_{ss} = 2.5R_s$), respectively. [2] So to predict solar wind speed out in the heliosphere, it is necessary to know B_{ph} and B_{ss} along each flux tube in order to calculate its f_s. Second, in the PFSS model, every magnetic field line traced downward starting from the source surface or further out is magnetically open to the heliosphere (i.e., is associated with a coronal hole). [4] A complete mapping of all field lines traced from the source surface/outer boundary down to the photosphere thus identifies, a least in principle, all of the coronal holes on the Sun. However, depending on the resolution of the grid used, cells on the photosphere that are magnetic open to the heliosphere are often missed when tracing the field in this manner. In previous versions of the model, this was fine because only the expansion factor was required to calculated solar speed. However, Arge et al. found a better empirical velocity relationship that was a function of two coronal parameters: (1) flux tube expansion factor (f_s) and (2) the minimum angular separation (θ_b) at the photosphere between an open field footpoint and the nearest coronal hole boundary. [4] & [11] The second coronal parameter requires an accurate model description of coronal holes because misidentifying grid cells that are actually magnetically open for ones that are closed becomes a serious issue. It is a problem because it results in coronal hole boundary distances (θ_b) that are too small and thus solar wind speeds that are too slow (i.e., small θ_b corresponds to low solar wind speeds and vice versa). Figure 2 highlights this problem. It shows two sets of three panels comparing WSA coronal model results before (left set) and after (right set) upward field line tracing was implemented in the model. The top left and right panels show the global photospheric magnetic field for Carrington Rotation 2050. The middle ones show the WSA predicted solar wind speed at 5Rs. The bottoms ones show the photospheric magnetic field polarity (i.e., gray scale) with the model predicted coronal holes (colored regions) plotted on top. The red/white plus signs near the equator mark the daily positions of the sub-earth points, while the black straight lines identify the connectivity between the outer (open) boundary located at 5.0 *Rs* and the source regions of the solar wind at the photosphere (1.0 *Rs*). Comparison of the two middle panel reveals a large slow solar wind region in the original WSA model results (left) not seen in the improved model (right) where the field lines are now also traced upwards from the photosphere. The slow wind region artifact is caused by cells on the photospheric field map being misidentified as closed in the southern polar coronal hole (i.e., bottom left panel in Figure 2). Clearly the solar wind speeds in the affected region are very low and rather inconsistent with the high speed solar wind expected to be emerging from such a large polar coronal hole near solar minimum. [12] As can be seen in the middle right panel of Figure 2, the upward field line tracing method clearly resolves the problem

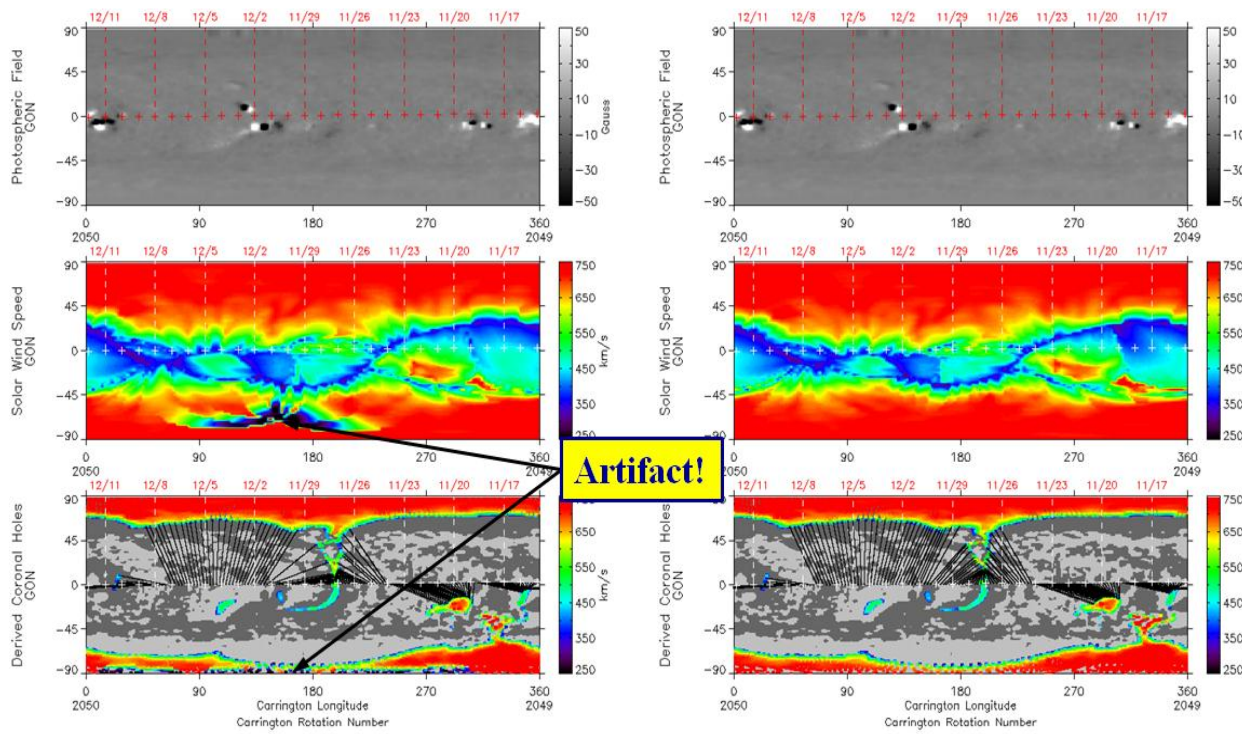

Figure 2. WSA Results Before (Left) and After (Right) Upward Field Line Tracing Implemented

The upward field line tracing methodology was incorporated into WSA early on in this effort and first appeared in model version 2.2. WSA 2.2 makes up the coronal portion of the WSA+Enlil model, which was recently transitioned to operations at the National Oceanic and Atmospheric Administration's (NOAA) National Centers for Environmental Prediction (NCEP). Both

NOAA/NECP and the Air Force Weather Agency routinely use this model for making their daily space weather forecasts. [13]

Finally, the new version of WSA, version 3.3, with all of the above described changes and improvements, was delivered to the AFRL Solar Disturbance Prediction Program located at Kirtland Air Force Base. The code was successfully installed, compiled, and confirmed to run properly.

5. CONCLUSIONS

Three major and several minor improvements were made to the coronal portion of the WSA model that has significantly enhanced the model's functionality and predictive capability. First the PFSS and SCS models were decoupled and modularized resulting in the need for only one version of the code thus making it much more flexible and significantly easier to maintain. Second, the code was modified so that predictions at other, non-ecliptic locations, can easily be made. Originally the code was designed to only make predictions at Earth. The third improvement made to WSA was the inclusion of outward magnetic field tracing from the photosphere to the outer coronal boundary of the model. Adding this capability greatly improves the model's ability to accurately predict the sizes, shapes, and positions of coronal holes and thus the solar wind. WSA 2.2, a version of the code with just the outward field line tracing fix incorporated into it (and not the other two changes), is part of the WSA+Enlil coronal and solar wind model that was recently made operational at NCEP. AFRL support for this work has thus already resulted in a practical space weather model that is routinely used by both the civilian and defense department branches of the United States government.

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List of Acronyms

AFRL	Air Force Research Laboratory
AFSPC	Air Force Space Command
AFWA	Air Force Weather Agency
MHD	Magnetohydrodynamics
NCEP	National Centers for Environmental Prediction
NOAA	National Oceanic and Atmospheric Administration
PFSS	Potential Field Source Surface (model)
SCS	Schatten Current Sheet (model)
SWPC	Space Weather Prediction Center
WSA	Wang-Sheeley-Arge

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